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Biomass resources to hybridize CSP with biomethane: potential of horticultural residues and drought-tolerant crops.

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Abstract

HYSOL technology allows the hybridization of Concentrated Solar Power (CSP) technology with biomethane for the efficient generation of clean and sustainable electricity in a firm and dispatchable manner. Biomass from horticultural residues and drought-tolerant crops is a promising feedstock for biomethane production in areas with high solar radiation. This paper investigates the biomass potential of these two resources in Spain by considering the volume of horticultural residues generated, availability of suitable land for dedicated prickly pear plantations and its methane generation capacity. Experimental biomethane yields have also been determined for different substrates mixtures of overripe tomatoes and prickly pear cladodes. Potential biomethane and electricity production are then calculated, as well as the number of conventional CSP and HYSOL plants that could be supplied with this energy. Results show that a significant number of CSP plant could be methane-supplied by the studied resources: up to 45 conventional CSP or 4 HYSOL plants.

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Keywords: CSP;HYSOL; GIS; methane; biomass; residues; Opuntia.

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1. Introduction

One of the major drawbacks of power generation in Concentrating Solar Power (CSP) plants is the discontinuous availability of the solar resource at the plant allocation. A useful strategy to overcome this problem is the hybridization of this technology with auxiliary fuels to supplement solar radiation when this is not available. Due to its fast response and low cost, natural gas (NG) is the most widely used auxiliary fuel in this type of plants, turning solar plants in a partially renewable energy production system. The HYSOL project (FP7-ENERGY-2012-1, CP 308912) aims to develop a fully renewable CSP plant where biomethane originated from biogas upgrading, rather than NG, is used to supplement solar radiation for extended, firm and dispatchable power generation.

Areas with a high availability of solar energy are often semiarid or arid areas (as clouds and atmospheric moisture interfere in the transmission and reception of Direct Normal Irradiation-DNI) where the potential for natural biomass production is limited due to poor soil quality and lack of water resources. Despite these difficulties, many arid and semiarid locations profit from their solar potential by developing intensive agricultural production systems based on the efficient use of underground or imported water, such is the case of Spain. These agricultural systems usually employ greenhouses, as they allow the application of advanced plant production technologies (such as temperature control, efficient watering or CO_2 fertilization), while facilitating pest control. The productivity of greenhouse intensive systems per unit of surface area is very high, but so is the amount of residues generated in the form of biodegradable organic matter. When these residues are not adequately treated, they generate a wide range of environmental problems: groundwater pollution, GHG emissions, healthy risks, bad odours, etc. Considering the fact that vegetables are the main product of the described agricultural systems[1], these residues usually contain high amounts of water and fairly high amounts of easily degradable carbohydrates, so they represent an interesting substrate for the production of biogas via anaerobic digestion.

These irrigated plantations are usually surrounded by wastelands where no conventional rainfed crops can be established due to aridity of the climate and the poor soil quality. However, certain crops adapted to these harsh environments can capture and store solar energy as carbohydrates for its subsequent transformation into biomethane. These crops resist high temperatures, water scarcity, and high levels of solar radiation, while having great water use efficiency (WUE) and can be cultivated in poor and shallow soils as energy crops. Prickly pears (*Opuntia spp*.) is the most typical of these species, achieving an optimum balance between WUE and biomass yield. Besides, prickly-pear biomass is rich in starch and pectin carbohydrates, and poor in lignin [2-5]. This composition makes it suitable for anaerobic digestion in relatively short retention times, as in commercial biogas plants. Prickly-pear biomass may be obtained as a secondary product from the pruning of fruit-dedicated orchards or from energy-dedicated crops where the stems (cladodes) are the main harvestable product.

The aim of this investigation is to quantify the availability of biomass from horticultural residues and drought-tolerant crops in Spain, to evaluate the potential of these products as substrates for biogas production and to assess the biomethane generation potential of both materials for its use in hybrid CSP plants in this country. Tomato has been used as horticultural crop for experimental determinations, as it represents 29 wt % of the total horticultural production in Spain[1]. *Opuntia ficus-indica* (L.) Mill. has been selected as drought-tolerant plant due to the commercial experience as a crop and also for being the highest yielding species in the *Opuntia* genus.

2. Materials and methods

2.1. Production of horticultural residues in Spain

In the present work only easily biodegradable horticultural residues have been taken into account. The availability of these residues was estimated considering the amount of horticultural crops withdrawn from the market due to the application of European policies and also those discarded for technical reasons (damaged, too or not enough ripen)[6].

2.2. Potential production of prickly-pear biomass in Spain

In this section, prickly-pear potential for biomethane production has been estimated for Spain. In order to reach this objective, the following steps were taken:

1. Surface area with already established prickly-pear fruit orchards was determined [1].
2. Yield of pruning residues per hectare has been estimated by Aranda *et al*. (2010) to be 10 t fresh matter/ha.[7]
3. Land surface with suitable climate conditions for the cultivation of prickly pear was estimated. By using a Geographic Information System (GIS) aided methodology, land was classified into three categories:
- *Non-suitable* (NS*)*: Those lands where prickly pear cannot be successfully cultivated because they meet one or more of the following criteria: Mean annual rainfall (P) < 200 mm [8], mean minimum temperature of the coldest month (t_1) < 3ºC [8], mean maximum temperature of the warmest month (T_{12}) > 42ºC [9].
- *Suitable for prickly pear (*SP*)*: Those lands suitable for the cultivation of prickly pear but not for other rainfed crops, where 200 < P < 450 mm, t_1 > 3ºC, and T_{12} < 42ºC.
- *Suitable for prickly pear and other crops* (SPOC): Those lands suitable for the cultivation of prickly pear and other rainfed crops, where P > 450 mm, t_1 > 3ºC, and T_{12} < 42ºC.
4. An underestimation coefficient representing the percentage of rainfed arable lands in Spain (14.1 %)[1]was applied to SP land surface in order to estimate the final amount of potential land for prickly-pear cultivation. After that, the area occupied by lands with already established prickly pear fruit orchards was subtracted.
5. Prickly-pear biomass yield was calculated according to an empiric formula using rainfall data. The following equation, proposed by Sánchez *et al.*[10], was used to estimate prickly-pear biomass yields in suitable lands:

$$Yield\left(tDM\ /\left(ha \bullet year\right)\right) = 0.0067 \bullet P^{1.1653}\left(mm\right)$$

Where yield is expressed in tons of dry matter (DM) per year, and P is annual rainfall. Mean rainfall in SP areas is considered to be 325 mm/year.

6. Mean dry matter content in prickly-pear biomass was estimated according to data from literature (9.4 wt %) [2-4].

As mentioned above, land suitable for the cultivation of prickly pear but not for other rainfed crops (SP) are lands where annual mean rainfall is above 200 mm (limit for the establishment of productive prickly-pear plantations) and below 450 mm. This latter value is the lowest considered[11] as necessary for the regular cultivation of barley, the most drought-resistant crop among the essential rainfed food-crops in Europe. This means that SP lands cannot be used for rainfed direct food production on a regular basis. For GIS assessment, climate datasets were compiled at 30 seconds resolution in ESRI format from the Global Climate Data, available at http://www.worldclim.org/ [12]. Map Algebra tools from ArcGIS™ (ESRI®) software were used for the estimation of lands suitable for growing prickly pear.

2.3. Experimental research: Biomethane potential of selected biomasses

2.3.1. Plant material

Spineless and mature prickly pear terminal cladodes were collected from feral (naturalized) specimens in the Madrid region (Spain). This would be the kind of biomass harvested in a dedicated prickly pear plantation used as energy crop. Overripe tomatoes from a pool of different varieties were obtained in a local Spanish grocery. Both biomasses were ground separately and stored at -18 ºC. The samples were characterized for their content of total solids at 103 – 105 ºC (EN 14774-2:2010), volatile solids at 550 ºC (EN 14775:2010), Chemical Demand of Oxygen (COD) and Soluble Chemical Demand of Oxygen (CODs) (ISO 6060:1989).

2.3.2. Biomethane potential experiments (BMP)

Biomethane potential experiments were carried out with prickly pear, tomato, and various combinations of both substrates (1:3, 1:1, 3:1 -*volatile solids weight: volatile solids weight*). Experiments were done according to standard method NDVI-4630. Essays were done in triplicate for each substrate and "blank" digestions with inoculum from a sewage treatment plant as sole substrate were also performed. An AMPTS II (*Bioprocess Control*) apparatus was employed to carry out digestions and determine methane potential. $KHCO_3$ was added to substrates in order to reach initial pHs between 7.00 and 7.04.

2.3.3. Biomethane potential from horticultural residues and prickly pear biomass

Once the total amounts of horticultural residues and prickly-pear biomass had been estimated and their respective BMPs had been determined, biomethane production potentials were estimated by considering their respective mean volatile solids (VS) contents, which were determined as 9.5 wt % fresh matter basis (f.m.b.)[6] and 7.4 wt% (f.m.b.)[2, 3]. Tomato BMP was assumed to be representative of the horticultural residues. The amount of biomethane required in a CSP plant depends on overall power generation and auxiliary fuel input. Two scenarios were considered in the analysis. First scenario involved a conventional 50 MWe CSP plant with 15 % biomethane input ($3.45 \cdot 10^5$ GJ CH_4/year, in terms of gross energy). Second scenario was a 100 MWe CSP plant with HYSOL technology and 55 % biomethane input ($3.40 \cdot 10^6$ GJ CH_4/year, in terms of gross energy). Heating value of biomethane was assumed to be 35.8 MJ/m^3. Figure 1 shows a flow chart of the methodology developed in order to achieve the aims of this work.

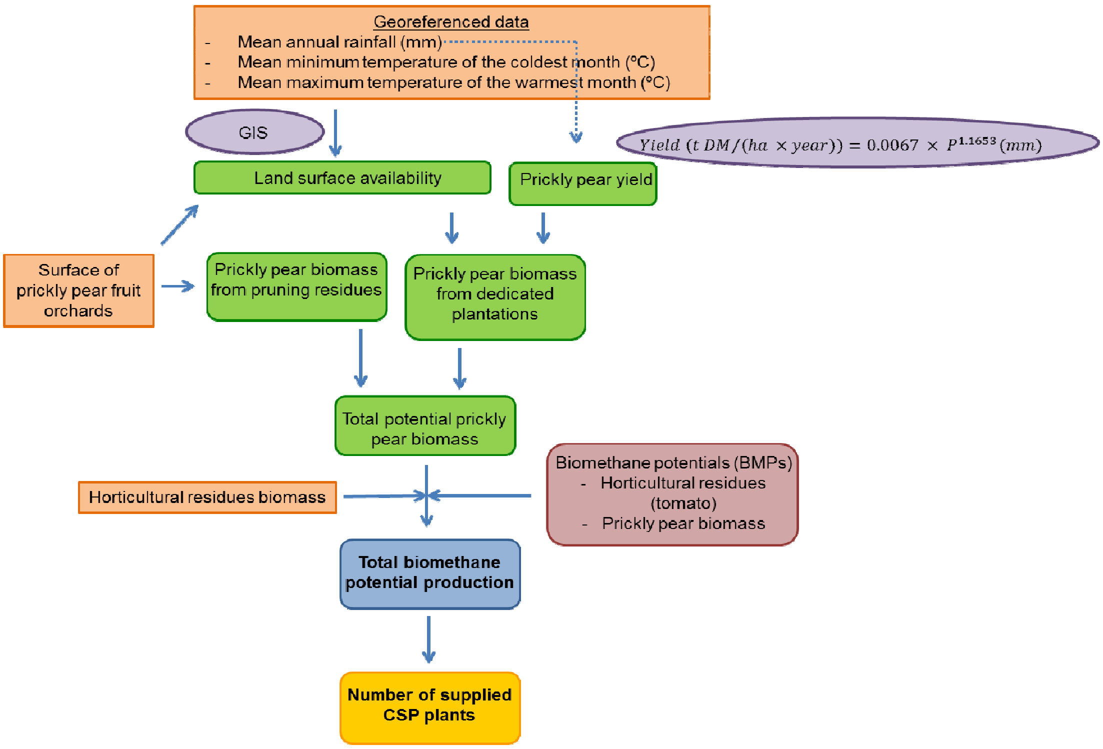

Figure 1 Flow chart describing the tasks and procedures followed in the present work

3. Results

3.1. Horticultural residues in Spain

The total amount of vegetables withdrawn from the market in Spain reaches 733,173 t/year (f.m.b.). Discarded vegetables may be estimated as 146,491 t/year (f.m.b.)[6]. This results in a total amount of residues of almost 880,000 t/year, 32.8 wt % of which may attributable to tomato production.

3.2. Potential production of prickly-pear biomass in Spain

3.2.1. Biomass potential from prickly-pear fruit-orchard residues in Spain

Prickly pear plantations in Spain total 514 ha, when including scattered plants[1]. This means a total estimated biomass in the form of pruning residues of about 483.16 t DM/year.

3.2.2. Potential biomass generation from dedicated prickly-pear crops in Spain.

Figure 2 shows the map of land suitability for prickly-pear cultivation in Spain, as produced using GIS. The results show that most of the lands suitable for prickly-pear cultivation but not for the establishment of other rainfed crops are located in the southeast of the country, in the provinces (NUT 3) of Alicante, Almería, Murcia, and Valencia. A significant percentage of these lands show a high solar potential for CSP (DNI ≤ 7.9 GJ/(m^2*year))[13].

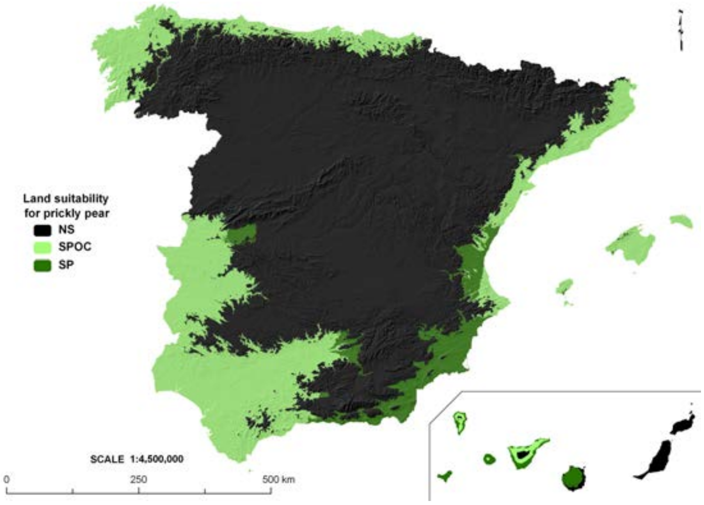

Figure 2. Land suitability for prickly-pear cultivation in Spain: NS: Non suitable lands; SPOC: Suitable lands for the cultivation of prickly pear and other rainfed crops; SP: Suitable lands for the cultivation of prickly pear but not for other rainfed crops (SP).

Considering the underestimation coefficient (14.1 %) applied to transform *suitable lands for prickly-pear cultivation* (SP) into potential lands for prickly-pear cultivation, a total value of 349,126 ha was determined, which represents 0.69 % of the country’s total surface. This value could be further reduced if other parameters (in addition to climate) had been considered, such as terrain slope, actual land occupation by crops, and the presence of Nature Conservation Sites. On the contrary, this value would increase if wastelands and abandoned lands corresponding to SPOC areas were included. These analyses would be site specific requiring the use of high resolution data, not always available. Regarding biomass yield, the previously mentioned equation was employed. This equation is adequate for Mediterranean climates and mean annual rainfalls between 150 and 500 mm, and estimates the biomass production for well-managed dedicated crops (where plants are five years old, at least). The calculated mean yield was 5.66 t DM/(ha*year). According to the proposed methodology, total biomass production from prickly pear energy-dedicated crops could reach 1,973,146 t DM/year.

3.3. Biomethane potential of prickly pear cladodes and residual tomatoes

Table 1 shows the results of the characterization of prickly pear cladodes and tomato fruits. The proportion of organic matter (expressed as volatile solids) over the total solids content is slightly higher in tomato (83 %) than in prickly pear (79 %). The soluble organic matter fraction (expressed as CODs) is also higher in tomato (66 % of COD) than in prickly pear (46 % of COD). Soluble organic matter is more accessible and more rapidly degraded by microorganisms, so this parameter has a high influence in the kinetics of the anaerobic digestion process.

Table 1 Total solids and organic matter content in prickly-pear cladodes and tomato fruits. COD: Chemical Oxygen Demand. CODs: Soluble Chemical Oxygen Demand

	Prickly-pear cladodes	Tomatoes
Total solids (wt %, f.m.b.)	6.3	4.8
Volatile solids (wt %, f.m.b.)	5.0	4.0
COD (gO_2/L)	69.7	69.3
CODs (gO_2/L)	32.0	45.8

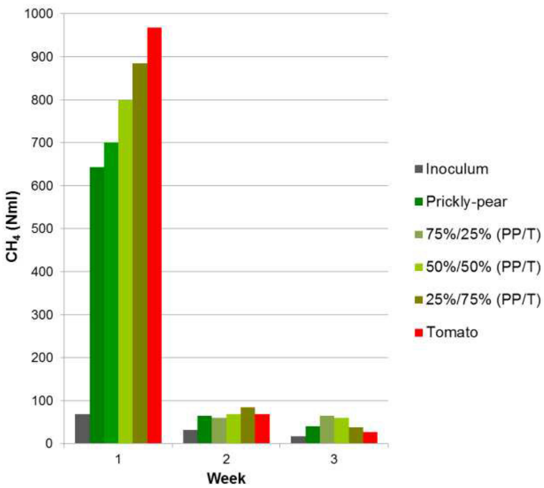

Figure 3 Weekly production of methane of the different substrates in the BMP experiments.

Figure 3 shows weekly methane production rates from the selected substrates and substrate mixtures. At BMP essays conditions, most of the methane (78 – 86 % of total) is produced in the first week. Due to its high content in easily biodegradable sugars[14, 15], substrates with higher tomato proportions produce more methane during the first week and less thereafter, suggesting the almost complete exhaustion of degradable solids. Table 2 shows the methane yields obtained from the substrates. A clear trend could be observed: The higher the percentage of tomato included in the mix, the higher the methane yield. Despite this fact, all the resulting biogas generation potentials are within the range typically reported for fodder maize, the most important feedstock in agroindustrial digesters (0.25 – 0.38 Nm^3 CH4/ kg SV)[16-18]. The lower methane yield achieved by substrates where prickly pear is the main biomass could be attributable to the higher lignin content of this biomass and also to epicuticular waxes (both of them almost indigestible compounds) in prickly-pear cladodes[2-4, 14, 15].

Table 2 Methane yield from the different feedstocks (expressed as average ± standard deviation).

Substrate	Biomethane potential (Nm^3 CH_4/ kg SV)
Prickly-pear (PP)	0.264 ± 0.011
75%/25% (PP/T)	0.275 ± 0.015
50%/50% (PP/T)	0.314 ± 0.011
75%/25% (PP/T)	0.341 ± 0.014
Tomato (T)	0.369 ± 0.017

3.4. Biomethane potential of horticultural residues and prickly pear biomass in Spain.

Table 3 summarizes the results obtained in this work. Horticultural residues in Spain can provide the total biomethane required by three conventional 50 MWe CSP plants where 15 % of electricity is generated from this gas. In case of a HYSOL 100 MWe CSP plant, the estimated amount of residues does not represent enough biomass to supply all the biomethane demanded by one plant, but it can contribute to a 33 %. Prickly pear plantations could produce sufficient biomass to supply biomethane for 42 CSP conventional plants or 4 CSP HYSOL plants. If both biomasses are considered together, 45 conventional CSP and 4 HYSOL plants could be methane-supplied. Considering a crop yield of 5.66 t DM/ha*year, each conventional CSP plant would requiere the biomass production of 8,205 ha of prickly pear energy-dedicated plantations, while each CSP HYSOL plant would need 80,761 ha of this crop to meet its needs.

Table 3. Biomethane potential, electricity production, and number of CSP plants that could be hybridized with biomethane from horticultural residues and prickly pear biomass in Spain.

	Biomethane (Mm3/year)	Gross Energy (GJ/year)	Number HYSOL plants	Number of CSP conventional plants
Horticultural residues	30.9	1106275	0.3	3.2
Prickly-pear biomass	410.0	14680037	4.3	42.5

The results represent the first approach at a macroscopic scale to the biomethane potential of horticultural residues and prickly pear biomass in Spain. Further research at a more detailed scale, including environmental and economic analyses, would be useful in order to determine the optimal allocation of solar plants under this approach, where biomass from agricultural residues and drought- resistant crops hybridizes with the solar resource in order to reach fully renewable power production in CSP plants. Locations in the Almería province may have priority attention, as more than 16 wt % of total horticultural residues in Spain is produced here and prickly pear potential biomass could reach near 503,000 t DM/year[10]. Regarding other countries where this approach could be of interest, Morocco is a country with an important horticultural production (5.8 Mt in 2013 [19]), and where near 900,000 ha of prickly pear could be established, according to our own ongoing research, inside and close to areas with a DNI between 7.6 and 9.4 GJ/(m^2*year)[13]. This surface is 2.5 times higher than the one estimated for Spain. Furthermore, near 45,000 ha of prickly pear orchards for fruit production are already established in this country, according to a general press source [20], which means an amount of 450,000 t of pruning residues. In Mexico more than 200,000 ha of prickly pear are cultivated for different uses and about a 25 % of them would be prickly pear fruit orchards producing 500,000 t/year of pruning residues in a country where more than half of its surface is receiving a DNI above 7.5 GJ/(m^2*year)[13].

Conclusions

- With a production close to 900,000 t /year, horticultural residues represent a significant source of organic residues in Spain suitable for biomethane production.
- Lands that are adequate for the cultivation of prickly pear but not for rainfed food crops represent a significant amount of useful surface for biomass production in Spain. These lands are usually allocated in areas with high solar radiation which are also suitable for the deployment of CSP.
- Residual tomatoes and prickly pear cladodes are optimum substrates for anaerobic digestion as their biomethane potential yields (0.369 Nm^3 CH_4/ kg SV and 0.264 Nm^3 CH_4/ kg SV, respectively) are within the range of those reported for fodder maize, the most important agroindustrial feedstock. About 80 % of these yields can be achieved with retention times below ten days.
- Horticultural residues in Spain can provide the biomethane required by 3 conventional CSP plants or 33 % of the biomethane required by a HYSOL plant.
- Potential biomass production from prickly pear in Spain could allow obtaining enough biomethane to provide energy to 42 CSP conventional plants or to 4 HYSOL plants.

References

1. Ministerio de Agricultura Alimentación, y Medio Ambiente: Anuario de Estadística 2014 (2015)http://www.magrama.gob.es/estadistica/pags/anuario/2014/AE_2014_Completo.pdf
2. Abidi, S., Ben Salem, H., Martín-García, A.I., Molina-Alcaide, E.: Ruminal fermentation of spiny (*Opuntia amyclae*) and spineless (*Opuntia ficus indica f. inermis*) cactus cladodes and diets including cactus. Anim. Feed Sci. Technol. 149, 333-340 (2009)
3. Retamal, N., Durán, J.M., Fernández, J.: Seasonal variations of chemical composition in prickly pear (Opuntia ficus-indica (L.) miller). J. Sci. Food Agric. 38, 303-311 (1987)
4. Sánchez, F., Curt, M.D., Barreiro, M., Fernández, J., Agüera, J.M., Uceda, M., Zaragoza, G.: Variability of Carbohydrate Content in Prickly Pear (O*puntia ficus-indica* (L.) Mill.) Cladodes. Proceedings of the 20th European Biomass Conference & Exhibition, 03 – 18 – 22 June 2012, Milan (Italy), 596-599 (2012).
5. Sepúlveda, E., Sáenz, C., Aliaga, E., Aceituno, C.: Extraction and characterization of mucilage in *Opuntia* spp. J. Arid Environ. 68, 534-545 (2007)
6. Alfonso, D., Brines, N., Peñalvo, E., Vargas, C.A., Pérez-Navarro, A., Gómez, P., Pascual, A., Ruiz, B.: Cuantificación de materias primas de origen vegetal. PSE-PROBIOGAS Desarrollo de sistemas sostenibles de producción y uso de biogás agroindustrial en España (2010)http://213.229.136.11/bases/ainia_probiogas.nsf/0/D06E61BC808DB150C125753F00572938/$FILE/Inf_cuantificacion_vegetal_11-03-2010.pdf
7. Aranda, G.O., Miranda, R.L., Flores, V.C., Hernández, M.O., García, U.G., Flores, B.H.: Enriquecimiento proteico del nopal para alimentación animal (2010)http://chapingo.mx/produccionanimal/images/stories/documentos/Tecnologias/14-Tecnologia-11-Nopal-08.pdf
8. Le Houérou, H.N.: Forage and fuel plants in the arid zone of North Africa the Near and Middle East. In: Wickens, G.E., Goodwin, J.R., Field, D.V. (eds.) *Plants for Arid Lands*, pp. 117-141. George Allen and Unwin, United Kingdom (1984)
9. Inglese, P., Barbera, G., Gugliuzza, G., Liguori, G.: Ecophysiology and fruit production of cultivated *cacti*. In: De la Barrera, E., Smith, W.K. (eds.) Perspectives in Biophysical Plant Ecophysiology: A Tribute to Park S. Nobel, pp. 153-166. Universidad Autónoma de México, México (2009)
10. Sánchez, J., Sánchez, F., Curt, M.D., Fernández, J.: Assessment of the bioethanol potential of prickly pear (*Opuntia ficus-indica* (L.) Mill.) biomass obtained from regular crops in the province of Almeria (SE Spain). Isr. J. Plant Sci. 60, 301-318 (2012)
11. Mateo Box, J.M.: Prontuario de Agricultura. Ministerio de Agricultura Pesca, y Alimentación y Mundi-Prensa, Spain (2005)
12. Hijmans, R.J., Cameron, S.E., Parra, J.L., Jones, P.G., Jarvis, A.: Very high resolution interpolated climate surfaces for global land areas. Int. J. Climatol. 25, 1965-1978 (2005)
13. GeoModel Solar: Direct Normal Irradiation Maps of different countries. http://solargis.info/doc/_pics/freemaps/1000px/dni/ (2014). Accessed 05/2015 2015
14. Guil-Guerrero, J.L., Rebolloso-Fuentes, M.M.: Nutrient composition and antioxidant activity of eight tomato (*Lycopersicon esculentum*) varieties. Journal of Food Composition and Analysis 22, 123-129 (2009)
15. Hernández Suárez, M., Rodríguez Rodríguez, E.M., Díaz Romero, C.: Chemical composition of tomato *(Lycopersicon esculentum*) from Tenerife, the Canary Islands. Food Chem. 106, 1046-1056 (2008)
16. Gunaseelan, V.N.: Biochemical methane potential of fruits and vegetable solid waste feedstocks. Biomass Bioenergy 26, 389-399 (2004)
17. Oslaj, M., Mursec, B., Vindis, P.: Biogas production from maize hybrids. Biomass Bioenergy 34, 1538-1545 (2010)
18. Vervaeren, H., Hostyn, K., Ghekiere, G., Willems, B.: Biological ensilage additives as pretreatment for maize to increase the biogas production. Renewable Energy 35, 2089-2093 (2010)
19. Food and Agriculture Organization (FAO): . http://faostat3.fao.org/browse (2013). Accessed 05/07 2015
20. Smith, S.: Cactus commerce boosts Morocco. http://news.bbc.co.uk/2/hi/africa/8166905.stm (2009). Accessed 05/15 2015